A downhole gravimeter can determine rock density in a natural gas storage cavern while it is in operation or still being solution mined.

Operating conditions or solution mining in progress preclude use of a standard density tool during conventional well-logging procedures.

Rock density is one of the principal input parameters for rock mechanical investigations in specifying optimum pressure levels in storage caverns.

Assessing load bearing

Designing underground cavities and especially planning for caverns in salt formations for storage require investigations of several questions that are posed in Fig. 1.

For the storage-cavern operator, maximum and minimum permissible operating pressures in a gas-storage cavern, along with geometrical design parameters, are the most important operating parameters. These two values determine the range of pressures which can be considered and are thus critical for the working-gas volume of the cavern.

Normally, a cavern operator wants to operate in a pressure range that incorporates the lowest minimum and highest maximum permissible pressures.

These parameters are critical for assessing the load-bearing ability and usability of a cavern.

In construction of the subsurface space in the salt rock, the stress field around the cavity is subject to considerable interference. This interference results from the difference in stress between the primary lithostatic pressure and the operational pressure in the cavern.

To guarantee the load-bearing capacity of the host rock, the permissible minimum pressure must be high enough to exclude the possibility of spalling of the cavern wall during the operating period.

Another important aspect, in a cavern field containing more than one cavern, is confirmation of the load-bearing ability of the pillars between individual caverns.

On the other hand, the maximum pressure must not exceed the value at which tensile stresses might occur in the cavern roof zone which could lead to fracturing of the rock and thus to loss of storage medium within the fracture system.

In addition, it must also be proven that the internal cavern pressure will not result in a large-scale increase of permeability of the rock salt— with the exception of a narrow zone immediately adjacent the cavern—which is otherwise considered to be technically tight. This must be proven because it might enable the stored gas to infiltrate the rock formation.

For rock mechanical determination, the minimum and maximum pressures depend critically on the existing stress state in the rock formation and thus on the rock densities of the layers adjacent to and overlying the cavern.

Density of the rock salt as host rock for storage can be determined somewhat precisely but not continuously in the laboratory within the framework of the lab tests carried out for the rock mechanical investigation.

On the other hand, even when extreme care is taken, determining the cover rock density on the basis of the conventional borehole logs (density logs plus additional petrological laboratory analysis, for example) still carries a degree of error.
As a result, the investigations always yield an upper and a lower limiting value for the rock density to be incorporated in the rock mechanical calculations. The previously mentioned influence of this value for determining the minimum and maximum permissible operating pressures makes clear that, from a safety point of view, the upper limiting value for the rock density is used for determining the minimum pressure; the lower limiting value, for determining the maximum pressure.

Ultimately, a large relative error in rock density means a reduction in the working-gas volume available for cavern operation, hence the requirement for optimization.

**Example calculation**

The importance of making the most accurate possible determination of the rock density for the geometrical design of a single cavern or a cavern field becomes clear in the following example of a gas-storage cavern (Fig. 2).

Designing either an individual cavern or a cavern field normally requires application of numerical methods to achieve the most realistic rock mechanical description, for example the finite element method (FEM).

This example, however, dispenses with complex numerical calculations and the associated assessment criteria. It instead concentrates on a rough estimate of the operating parameters $p_{\text{min}}$ and $p_{\text{max}}$, only to give an impression of the influence of the rock density.

The cavern considered here is at a depth of 1,200-1,600 m and has a volume of 500,000 cu m.

To prevent both fracturing of the host salt rock in the cavern roof area as well as any extensive infiltration of the rock mass by the storage medium, this example assumes the maximum permissible operating pressure to be 80% of the lithostatic overburden pressure at the casing shoe, thus leaving a safety margin to the stresses in the rock.

The permissible minimum pressure is selected so that for a limited time at the so-called "reference depth," a maximum pressure differential of, in this case, 25.0 MPa is present between the internal cavern pressure $p_{\text{min}}$ and the formation pressure acting at this depth.

The "reference depth" is the location of the maximum stress and lies approximately one third of the cavern height above the base of the cavern.

Table 1 shows the actual measured values of the cover rock and the rock salt densities. For the density of the cover rock, a relatively large error of $\pm 3\%$, in one case, and a relatively low error of $\pm 1\%$, in another case, are taken into consideration.

An error of $\pm 1\%$ is assumed in both measurements for the density of the more homogeneous rock salt.

These values are possible results when applying the measurement methods dis
Density probe with an enlarged caliper arm (foreground; Fig. 4).

cussed presently. As mentioned, the permissible minimum pressure is based on the higher density value, and the permissible maximum pressure is based on the lower density value.

In this example, minimization of the fluctuation range caused by imprecise density assessments allows an increase in working-gas volume of more than 7%.

It can be clearly seen that the most accurate possible determination of rock density is important from a rock mechanical point of view, not only because of the safety repercussions (load bearing and usage verification) but also for economic reasons (working-gas volume).

**Alternative methods**

In 1992, KBB was requested to propose a method for determining the density of the cover rock as a principle parameter in determining the pressure gradient. Consideration was given both to lab methods as well as to in situ measurements:

- Lab methods require sample-taking in the form of conventional coring, selection of cuttings, or taking other material samples using well tools such as core guns (Fig. 3).

In all cases, one must remember the possibility of a change in the material compared to in situ conditions due to relaxation of samples at the surface and other changes of the internal structure of the material during recovery or in the laboratory.

Nevertheless, this procedure is undoubtedly useful for gaining viable data, primarily against a background of a relative method of viewing.

- In situ measurements have the advantage that the rock mass is encountered in a comparatively original state. There are two possible alternatives to be considered here.

The most common is the density log, whose measurement principle is based on the variable absorption of artificially induced gamma radiation (usually emitted from a Gesium-137 source) by the rock depending upon its mass. The main interference factor has been found to be larger wash outs created during drilling and common, for example, in the weak clastic sediments of the Quaternary and Upper Tertiary in Northern Germany.

For such a measurement, a special enlarged caliper arm is used (Fig. 4) because diameters of more than 30 in. must be taken into account.

On the other hand, such a tool design could make the probe unstable and thus allow false readings.

In such well sections, assumptions must be adopted for the cover rock. A combination of such lab methods as porosity determination, microstructural evaluation, and petrology of the rocks is employed to achieve maximum reliability.

It must be pointed out, however, that the depth of penetration of these methods is limited to the immediate near zone to the well and cannot be carried out in cased wells.

Use of a gravimeter tool can offer another alternative.

**Gravimeter**

The borehole gravimeter meter itself is a sensitive spring balance. The equilibrium condition for the scales is such that any torques acting on the beam must be equalized out (Fig. 5).³

The following expression applies:

\[
\frac{\Delta m}{m} = \frac{\Delta F}{F}
\]
A lubricator is located atop a gas cavern well head that is depressurized before the probe is withdrawn (Fig. 7).

\[ D_m + D_r = 0 \]

where:

- \( D_m \) = The torque of the specimen mass (m) at distance (a) from the axle of rotation (Fig. 5)
- \( D_r \) = The returning torque applied by the torsion spring and the measuring spring which acts at distance (b) from the point of rotation (Fig. 5).

The measurement spring has the effect of always returning the beam to its original position (\( \alpha > 0 \)).

The measurement principle is based on the attractive force between masses (which is normally noticed as gravity).

Within areas accessible by drilling, the latter increases with increasing depth. In homogeneous media, this is a uniform phenomenon.

Deviations occur, however, in the heterogeneous crust of the earth and are caused by variations in density. It is this fact which the system exploits to determine the distribution of density of the rock mass.

In the case of pressure gradient determination in rocks, the greater penetration offers a substantial advantage. Whereas with a density probe one can assume \( 6 \) in. penetration, the gravimeter is influenced by the rock mass in a radius of several tens of meters (Fig. 6).

This means that inhomogeneities near the well but not encountered by the well, which could influence the rock pressure above a cavern, are brought into consideration. In addition, infiltration by mud and caliber variations are negligible because of their small volume compared to the rock mass in question.

A major advantage is the use of the probe in a cased well section. This means that logs can be run in wells already completed and in operation.

Thresholds are given, in part, because of well temperatures (Table 2). In the case of temperatures up to \( 110^\circ \) C., low-temperature units are used with outer diameters of only \( 3.75 \) in. At high temperatures of up to maximum \( 250^\circ \) C., the probe must be clad in a Dewar unit. This increases the diameter to \( 4.75-5.25 \) in. These figures also specify the minimum internal diameter of completion.

Furthermore, a pressure level of \( 140 \) MPa cannot be exceeded but is well within expected maximum gas pressures.

Finally, the well inclination also plays a major role. In sections of inclination greater than \( 14^\circ \), a gravimeter log is not feasible because of the spring-balance mechanism of the gravimeter itself.

For average densities only, however, it is quite sufficient to take only two measurements. In the case of, for example, an S-shaped well line, as those found in cavern cluster installations, the measurements are made in the vertical sections above and below the S section. Only the difference in gravity between the uppermost and the lowermost measurement is of interest for the calculation of the mean density.

Further infill measurements verify the structural model.

The advantages of the gravimeter for determining average rock densities are to be found on the one hand, therefore, in the larger depth...
of penetration and on the other hand in its applicability to cased wells, and finally in the generally negligible influence of the near zone, which may be subject to extreme caliber variations, mud infiltration, and the previously referred to casings.

**Measurements**

In drawing up a logging program, discussions will be required prior to the measurements to clarify the geographic situation, the geological model, and the selection of the strata for investigation. Furthermore, a mobilization of approximately 1 week needs to be taken into consideration.

The actual duration of the logging depends on the number of log points within the borehole. Experience suggests that 1 day is required for each cavern location.

The question of time is of relatively minor significance, however. The measurements can be carried out completely independently after the conclusion of all drilling and completion work.

It is therefore unimportant here whether the cavern is in the stage of solution mining or even in gas operation. For the latter case a lubricator is required (Fig. 7). The company carrying out the logging (Edcom) provided the tool; Schlumberger delivered the wireline truck and lubricator. KBB was consultant for the cavern-field operator.

Finally, a crane is needed for performing the measurements.

Logging is carried out at selected depths where the tool is held stationary until it stops oscillating.

The data are recorded after minimizing the scatter and then further processed to incorporate the exact geographical position and the location-specific earth gravity field.

Also considered are tide and morphology effects which influence the measurements due to different mass distribution at the surface and varying tidal forces.

In principle, two measurement points suffice to determine average density. Other positions, oriented on the lithostratigraphic data, serve to check the respective structural model set-up (Fig. 8), which is in turn integrated into the correction algorithm.

The model must reflect the fact that the nonuniform geology causes disturbances of the earth's gravitational field and thus produces only an apparent density reading. Choosing the wrong model would cause an error which depends on the density contrast of the formations and can lie in a range of zero to a few percent.

In the ideal case of horizontal bedding with uniform material properties, the gravimeter shows values identical to those of the density log.

A precondition here is that the well have suitable conditions; primarily no density contrast between formation water and mud and a uniform caliber of lowest possible diameter. This is advantageous with respect to the short distance reading within the immediate bore-
hole zone (invaded zone). In addition, for the density probe, the material should not be too complex. Otherwise the lithology correction required by the measurement principle (log density × lithology correction factor = bulk density) makes for over complexity because it is mineral dependent.

In the cases presented, sections are prepared in the cover rock, the caprock, as well as in the salt. Within the cover rock (Fig. 9a), the density log first provides usable data from a depth of approximately 20 m downwards because above this depth the zone is shielded by the conductor pipe. Beneath this depth, the trends show almost complete agreement. The absolute values of the gravimeter, however, were approximately 0.1 g/cu cm (approximately 5%) higher. It should be noted here that because of calibration problems and the difficulty of assessing mud infiltration into the poorly consolidated material, the densities yield slightly lower values, as could also be confirmed in a neighboring borehole.

As a result, the overall density for the cover rock from the gravimetric logging (2.15 g/cu cm) was used for the rock mechanical investigation. These values are approximately 2.5% above those of the density log values (2.10 g/cu cm).

In the second comparison (Fig. 9b), the density tool was run within the salt and the caprock. The overlying zone was cased. At the time, the interest was in logging only the salt zone. The question of determining the overlying rock density only arose after the cavern was already being solution mined. The gravimeter measured the borehole zone from the surface to the setting depth of the last cemented casing shoe and was run within the solution mining string.

The caprock gave identical values. Salt, after lithological correction of the log-densities, had one section with comparable data and another one with a slight variation. In this zone the gravimeter showed 0.01 g/cu cm (approximately 0.5% higher values). This was caused by an anhydrite zone clearly recognizable in the density log.

The good agreement was achieved because of good borehole geometry and no deleterious effects of the mud. The advantages and disadvantages of the system, as well as of the technical logging procedures, follow.

The gravimeter tool:
• Measures rock densities up to approximately 20 m into the formation
• Logs through casing (independent of a drilling rig)

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